Joining and Integration of Silicon Carbide-Based Ceramic Materials for Aerospace Applications: An Overview

Michael C. Halbig[1] and Mrityunjay Singh[2]

[1]**NASA Glenn Research Center,** Cleveland, OH
[2]**Ohio Aerospace Institute**, Cleveland, OH

47th International Conference and Exposition on Advanced Ceramics and Composites
Daytona Beach, Florida, January 22-27, 2023.

Emerging Materials & Sustainable Manufacturing Technologies Symposium in Honor of Dr. Tatsuki Ohji.

Outline

- Introduction
  - Objectives, Benefits, and Applications

- NASA GRC Joining Technologies for SiC-based Ceramics: monolithics and CMCs to themselves, each other, and to metals.
  - ➢ Brazing
  - ➢ ARCJoinT - Affordable, Robust Ceramic Joining Technology
  - ➢ Diffusion Bonding
  - ➢ REABond - Refractory Eutectic Assisted Bonding
  - ➢ SET Joining - Single-Step Elevated Temperature Joining

- Summary/Conclusions

Objectives

- **Deliver the benefits of ceramics and ceramic matrix composites (CMCs) for aerospace applications**:
  - Higher temperature capability.
  - Reduced cooling and weight.
    - Contributes to increased fuel efficiency, performance, range, and payload, and lower emissions and lower operation costs for future engines.

- **Develop joining and integration technologies**
  - Enable the wider utilization of ceramic matrix composite (CMC) turbine engine components by allowing for the fabrication of complex shaped CMC components and their incorporation within surrounding metal-based systems.

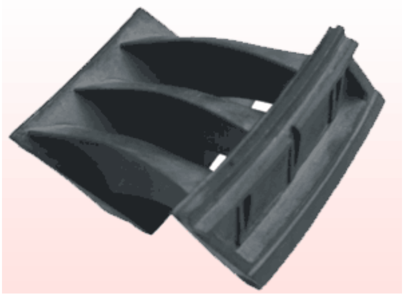


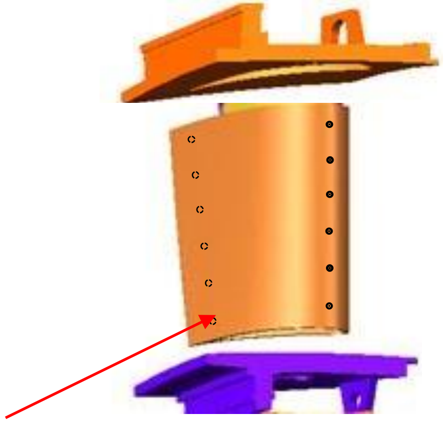


CMC Turbine Engine Components and Joining Needs

NASA Aeronautics Research Six Strategic Thrusts

3. **Ultra-Efficient Commercial Vehicles**
   - Pioneer technologies for big leaps in efficiency and environmental performance
4. **Transition to Low-Carbon Propulsion**
   - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology



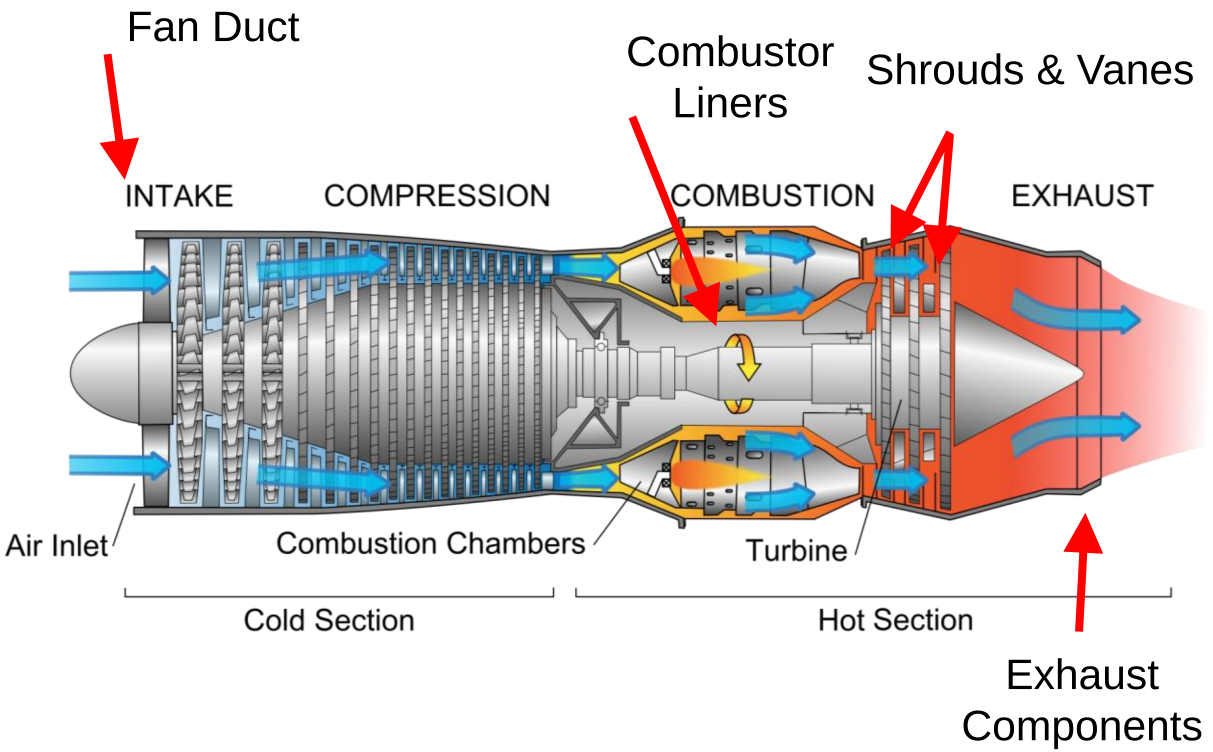


Joining of singlet vanes to form doublets and joining of vane airfoils to ring sections (for smaller engines)
- Allows for a reduction in part count, seals, and leakage

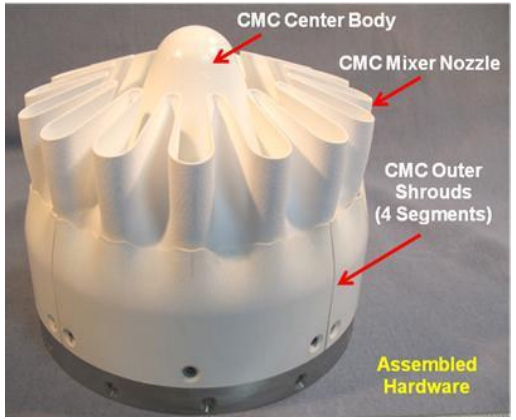
Joining of airfoil and end caps
- Easier fabrication compared to a continuous 3-D CMC vane

Components for Turbine Engine Applications

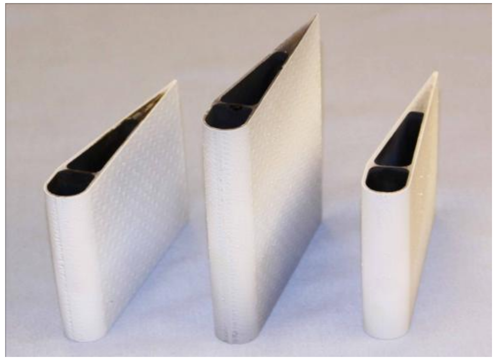
Turbine Engines - Targeted Components (CMCs)



NASA CMC Components



Oxide/Oxide Mixer Nozzle



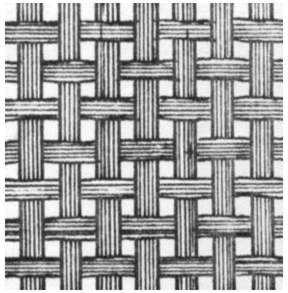
EBC Coated SiC/SiC Vanes

SiC/SiC Combustor Liners: Outer Liner and EBC Coated Inner Liner

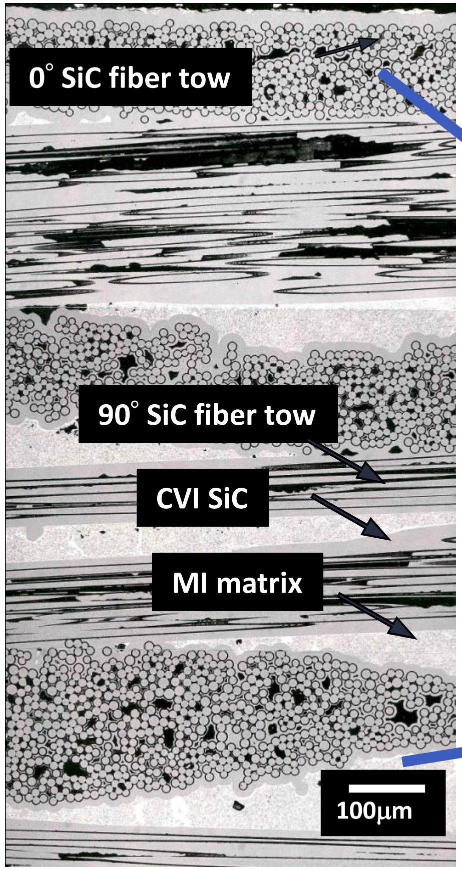
M.C. Halbig, M. Jaskowiak, J. Kiser, and D. Zhu. "Evaluation of ceramic matrix composite technology for aircraft turbine engine applications." In *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, p. 539. 2013.

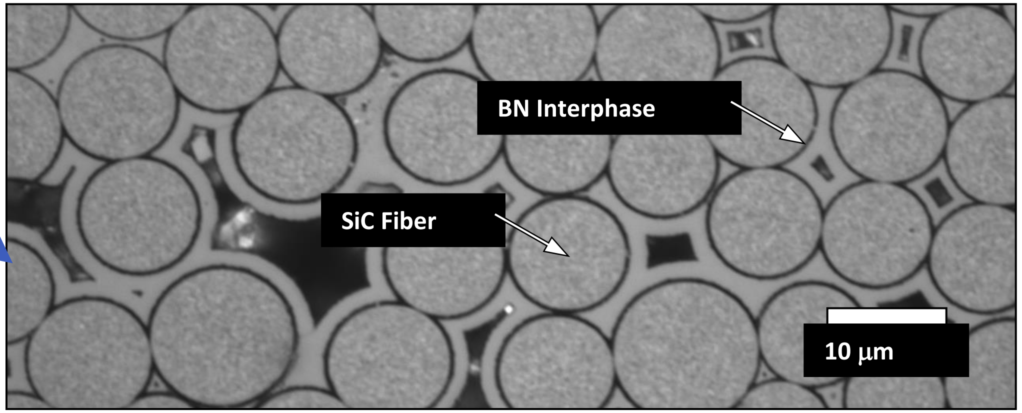
Conventional CMC Materials – Hybrid CVI and Melt Infiltrated (MI) SiC/SiC

0-90 Plain Fiber Tow Weave

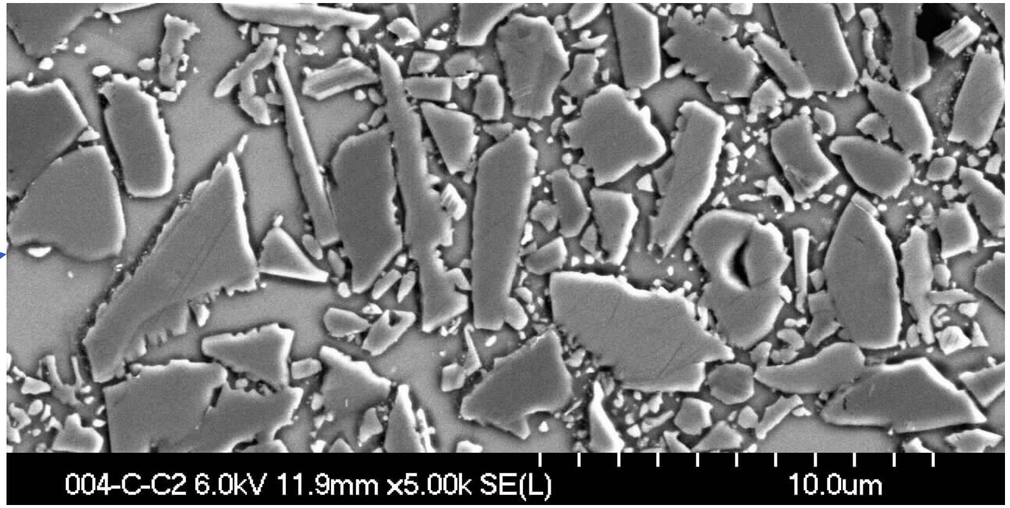


Composite Cross-Section





SiC fibers within a tow

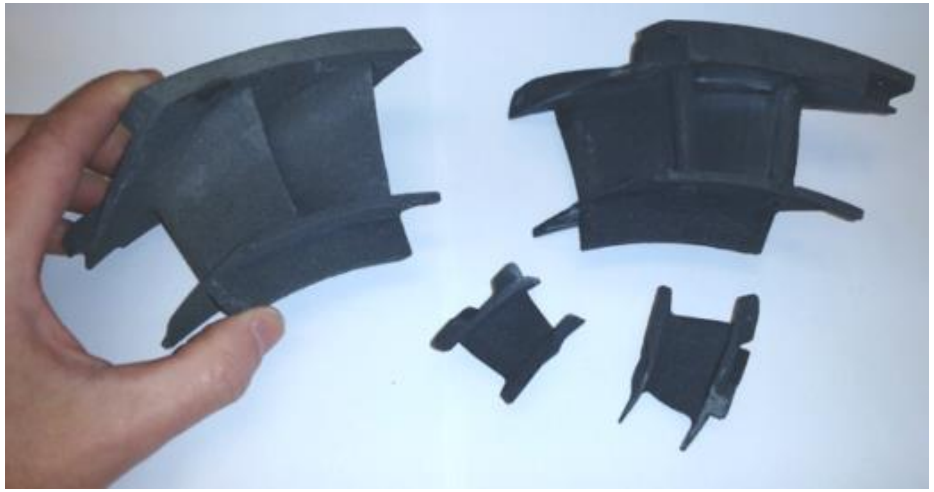


SiC grains and silicon within MI matrix

- High thermal conductivity matrix
- Elimination of interlaminar porosity
- No matrix micro cracking
- Continuous fibers and fracture toughness

Additively Manufactured SiC Fiber / SiC Matrix Composites Through Binder Jetting

ExOne Innovent



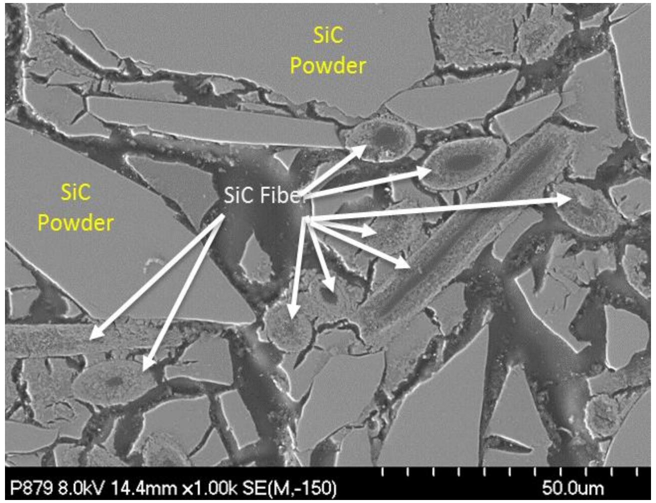
High pressure turbine cooled doublet vane sections.

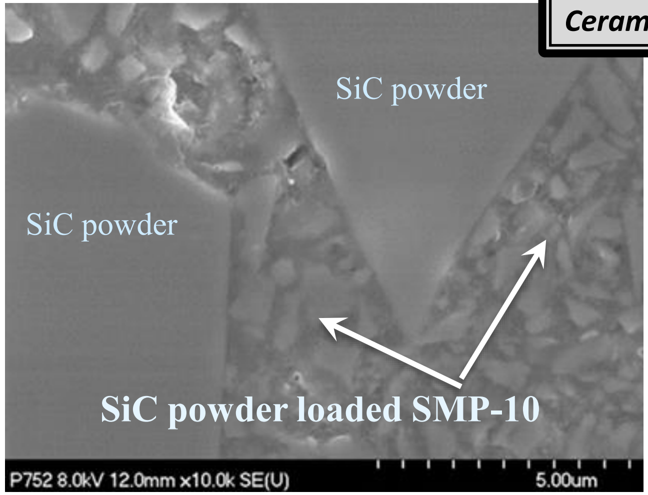
Demo of a complex component, however the material is currently only suitable for lower stress applications.

M.C. Halbig, J.E. Grady, M. Singh, J. Ramsey, C. Patterson, and T. Santelle. *A Fully Nonmetallic Gas Turbine Engine Enabled by Additive Manufacturing of Ceramic Composites*. No. E-19153. 2015.

Constituents

~70 μm long and ~7 μm in diameter

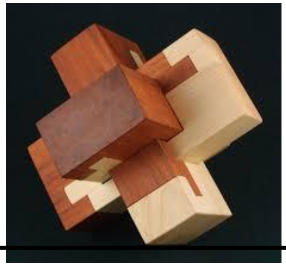




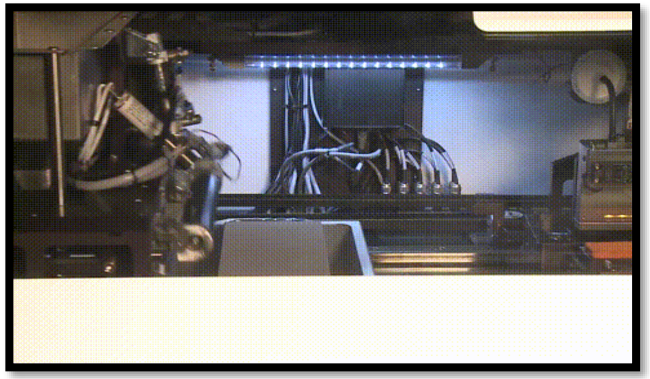
Short Fiber Reinforced Ceramic Matrix Composite

AM of fiber reinforced CMCs is in the early stages within the advanced processing field.

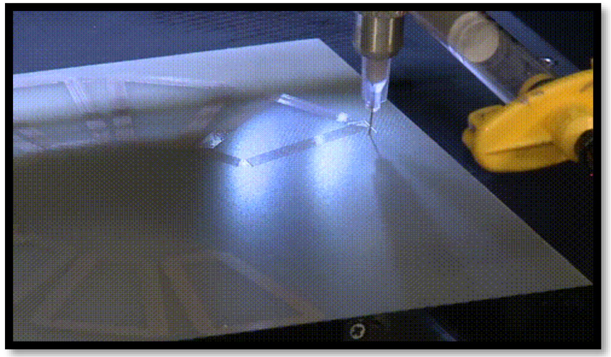
Comparison of Layerwise Fabrication Methods for Ceramics



Characteristics	Joining	Additive Manufacturing
Waste compared to machining	Less	Less
Internal features	Yes	Yes
Part count	More	Less
Multiple fabrication steps	Yes	Depends
Ceramic Matrix Composite (CMCs)	Uses Conventional CMCs	Non-mature CMCs
Maturity Level	Relatively High	Relatively Low
Multimaterial structures	Easier	Harder
Structural ceramics	More Robust	Less Robust

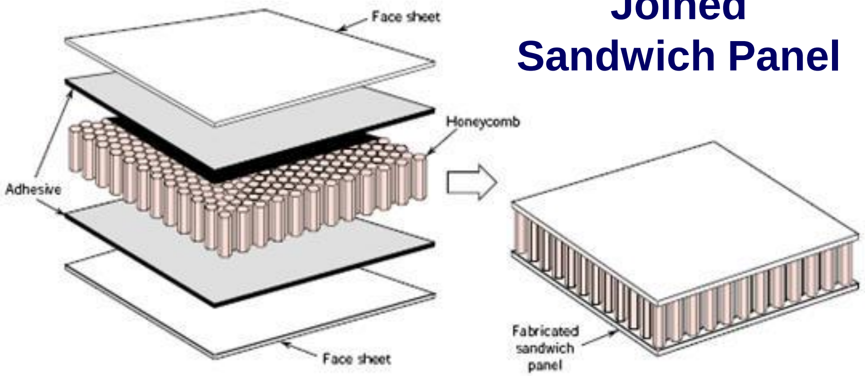


Binder Jet 3D Printing

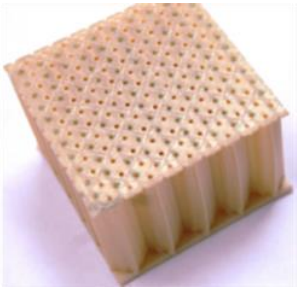


Direct Write Printing

Joined Sandwich Panel



AM Polymer Sandwich Panel



AM is more challenging for fiber reinforced materials, multi-materials, co-processing, and robust structural ceramic parts.

Joining and Integration of Ceramics and CMCs for Aerospace Applications

Development Approach

- Develop single, multiple, and hybrid interlayer approaches to aid in the joining of ceramics and CMCs to themselves and to metals.
- Optimize processing conditions so that joints and parts remain strong and crack free.
- Investigate inter-relations between processing, microstructure, and properties.
- Evaluate the thermal and mechanical properties of the joint.
- Scale-up of processing to larger and more complex shaped sub-components.
- Evaluate joints in relevant conditions which are comparable to engine operating environments.

Integration and Joining Technology Development

Ceramic to Ceramic (CMC to CMC) Systems:

- **Brazing** - liquid metal flows into a narrow gap between the mating surfaces and solidifies to form a permanent bond. *Also for ceramic to metal joining.*
- **High Temperature Reactive Joining** - two step reactive formation of high temperature capable joints using carbon paste and Si infiltration **(ARCJoinT).**
- **Diffusion Bonding** - mating surfaces are pressed together and heated to cause bonding by interdiffusion of the components.
- **Refractory Eutectic Phase Bonding (REABond)** - melting of a eutectic phase from a solid to a single-phase liquid.
- **Single-step Elevated Temperature Joining (SET)** - single step reaction formed SiC joint for >2400°F applications using C, Si, and SiC-based slurries.

Uniform, dense, crack-free joints from all approaches.

Comparison of CMC Joining Approaches

Characteristics	Joining Approach				
	Brazing (Cu-Si-Ti based)	ARCJoinT	Diffusion Bonding (Ti)	REABond (Si-Hf)	SET Joining (C,Si,SiC based)
Temperature limit	<1472°F (800°C)	<2400°F (1316°C)	~2373°F (1300°C)	<2400°F (1316°C)	>2400°F (1316°C)
Little or no processing pressure	√	√	x	√	√
Curved shape joining	√	√	x	√	√
Simple, one-step processing	√	x	√	√	√
Substrate surface condition	smooth or rough	smooth or rough	smooth	smooth or rough	smooth or rough
Ceramic or metal joining	both	ceramic	ceramic	ceramic	ceramic
Interlayer type	foils, pastes	pastes	foils, surface coatings	pastes, tapes	pastes, tapes
Cure CMC processing flaws (e.g. porosity and microcracks)	x	√	x	√	√
Issues	possible formation of brittle ceramic phases	free silicon	geometry limitations and processing stress	silicon rich phase	early in development
Bond quality	uniform, dense, and crack-free joints	uniform, dense, and crack-free joints	uniform, dense, and crack-free joints	uniform, dense, and crack-free joints	uniform, dense, and crack-free joints

Several joining approaches are available for various material pairings and application requirements.

Diffusion Bonding, REABond, and Brazing Joining Processes

Materials (dimensions 0.5” x 1”)

- Substrates: CVD SiC, SA-Tyrannohex (parallel), and SA-Tyrannohex (perpendicular).

- **Interlayers: Ti foil (10, 20 micron) and B-Mo alloy foil (25 micron)**

Ceramic substrates were ultrasonically cleaned in Acetone for 10 minutes

Substrates were sandwiched around braze and foil layers

Materials (dimensions 0.5” x 0.5”)

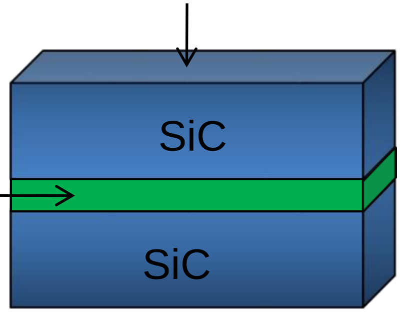
- CMC materials: C/C, MI SiC/SiC, CVI SiC/SiC, prepreg MI SiC/SiC, and SA-Tyrannohex.

- **Interlayer: Si-Hf Eutectic tapes of 1, 2, and 3 layers.**

- **Brazes: single layer, multi-layer, and tailored.**

Diffusion Bonding

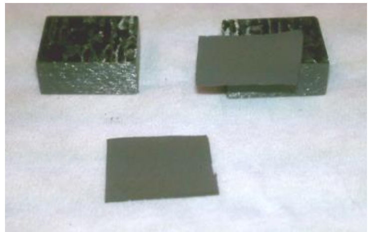
- Atmosphere: Vacuum
- Temperature: Ti 1200°C, B-Mo 1400°C
- **Pressure: 30MPa**
- **Duration: 1-4 hr**
- Cool down: 2 °C/min



REABond and Brazing

- Atmosphere: Vacuum
- Temperature: Reabond: 1340°C
 Brazing ~10°C above the braze liquidus temperature.
- **Load: 100 g/sample**
- **Duration: 10 minutes**
- Cool down: 2 °C/min

- Mounted in epoxy, polished, and joints characterized using optical microscopy and scanning electron microscopy with energy dispersion spectroscopy analysis.
- Thermomechanical analysis



Joining prep with CMC substrates and Si-Hf REABond tapes with 30-35% solid loading.

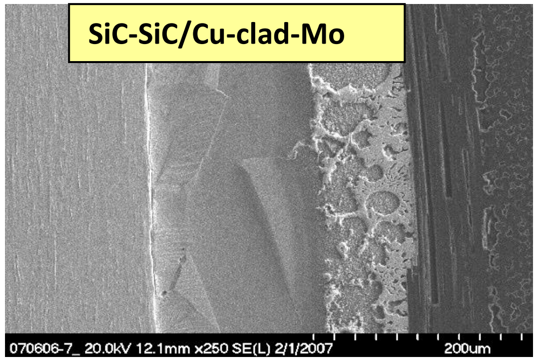
Material definitions:

CVD SiC => chemically vapor deposited SiC

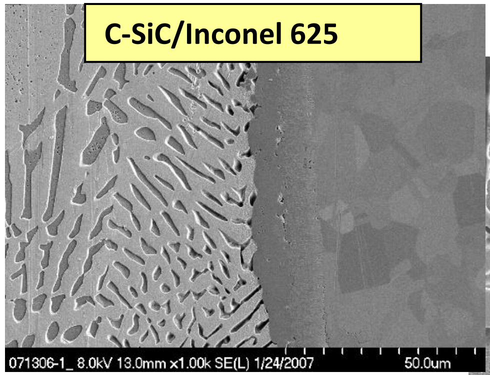
SA-Tyrannohex => Woven SA-Tyranno fiber hot pressed composite like material

Brazing: Ceramic to Ceramic and Ceramic to Metal Systems

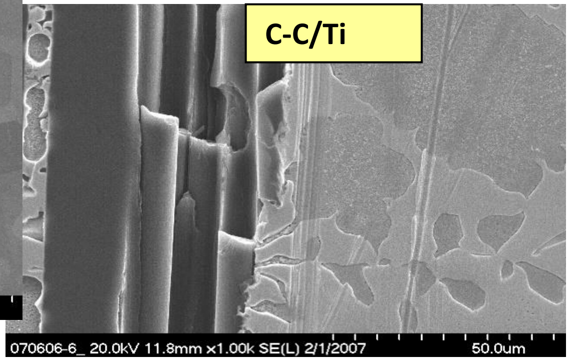
SiC-SiC/Cu-clad-Mo



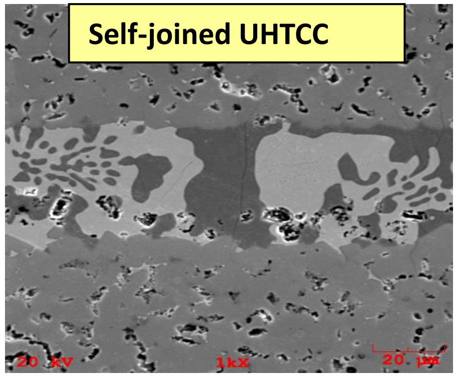
C-SiC/Inconel 625



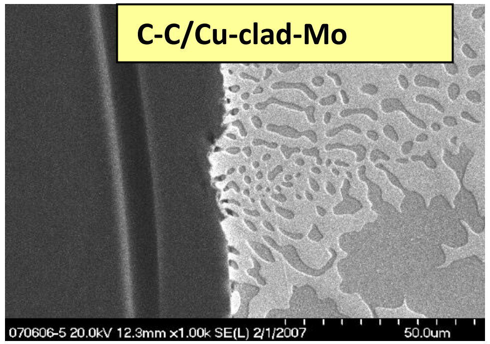
C-C/Ti



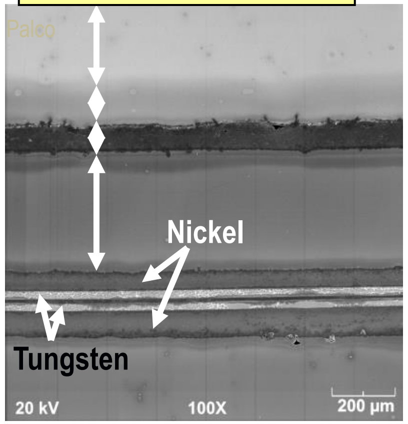
Self-joined UHTCC

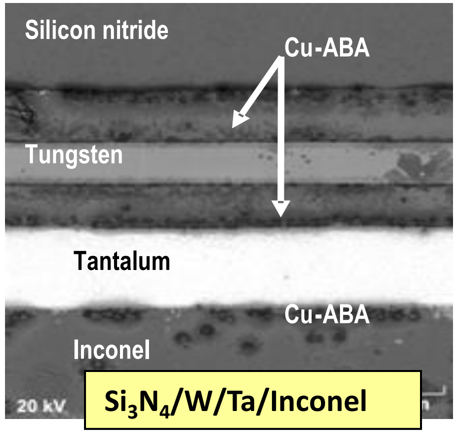


C-C/Cu-clad-Mo

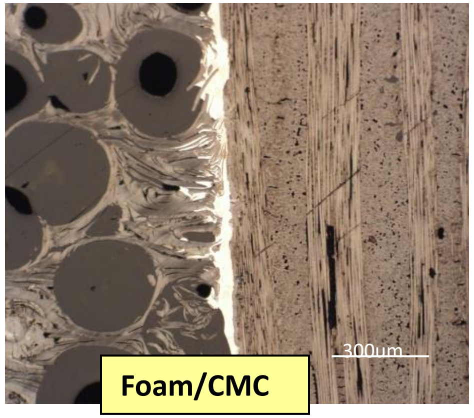


Si_3N_4/Ni/W/Inconel



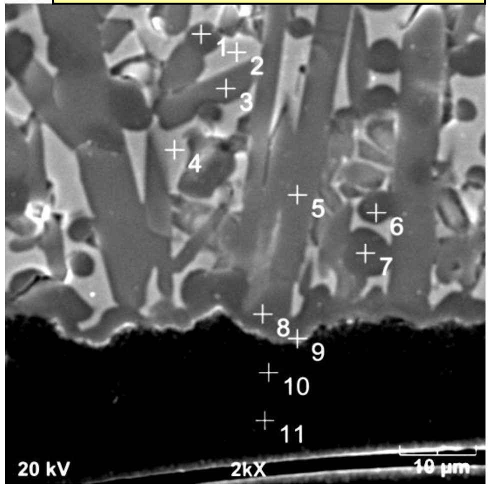


Si_3N_4/W/Ta/Inconel

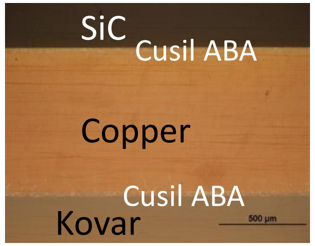


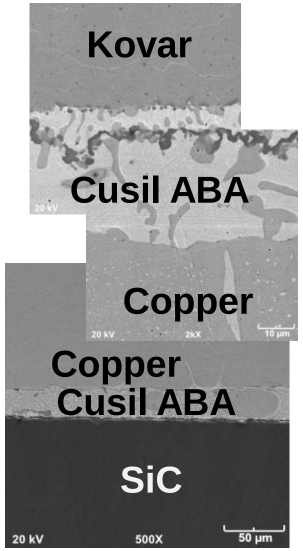
Foam/CMC

SiC-SiC/braze/Si-X/Inconel
(X: B, Y, Hf, Cr,Ta, Ti)



SiC/multi-layer/Kovar





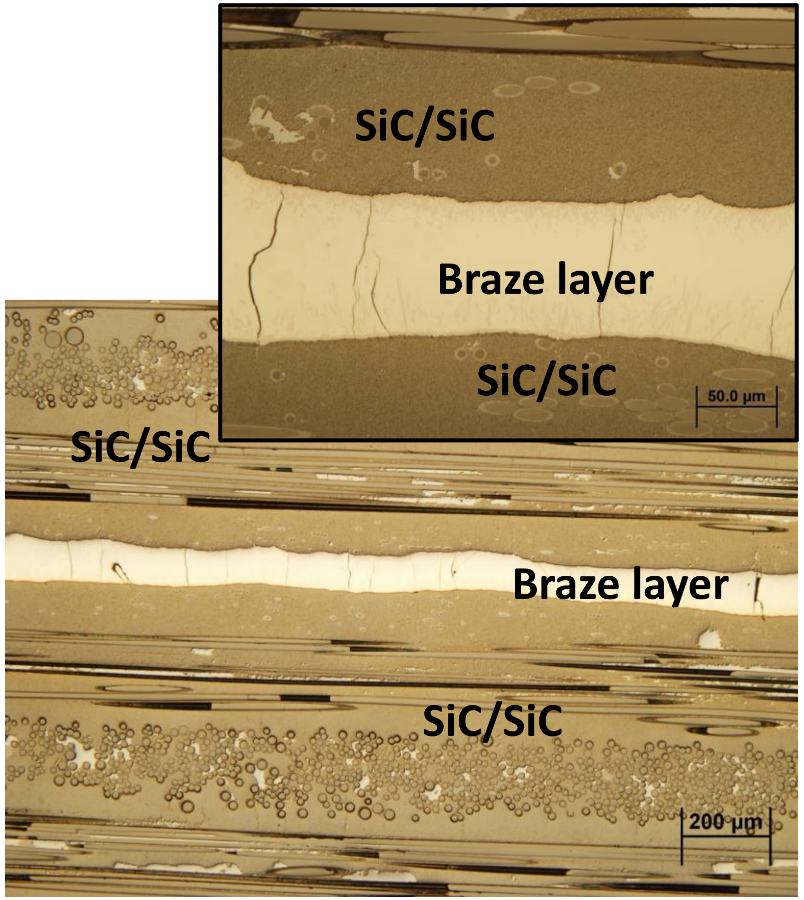
SiC/multi-layer/Kovar tubes

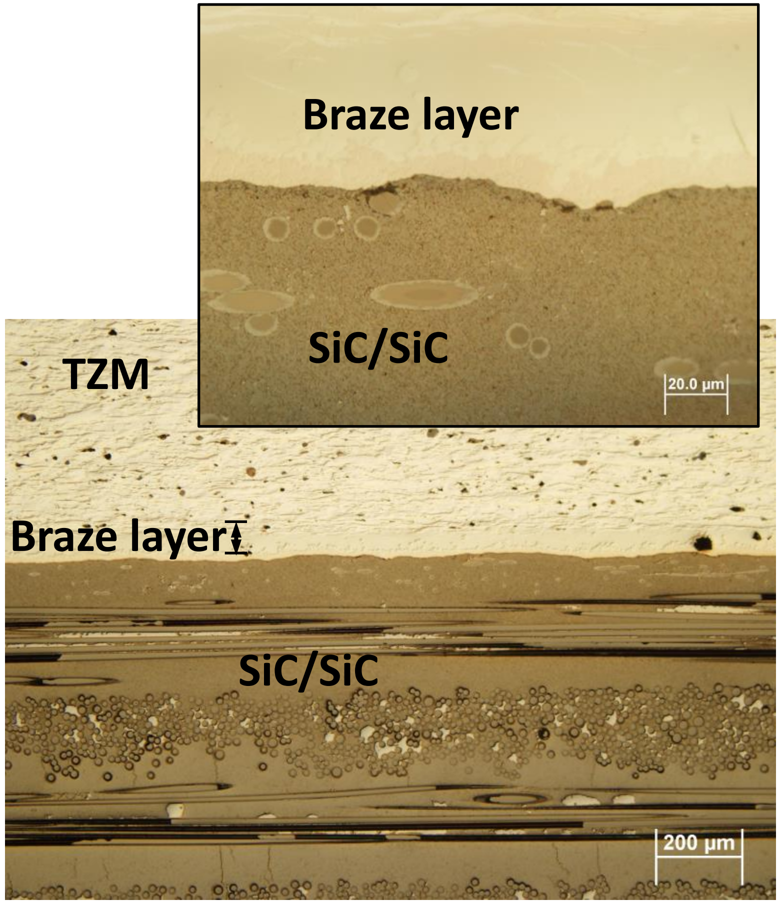
Design and Understanding of Interfaces is Key to Successful Integration

Successful brazing with many material combinations.

Brazing: CMCs to CMCs and to Metals

- Brazing of SiC/SiC to SiC/SiC and TZM
- TiBraze 200 foil: Ti(40)-Zr(20)-Cu(20)-Ni(20) in wt. %





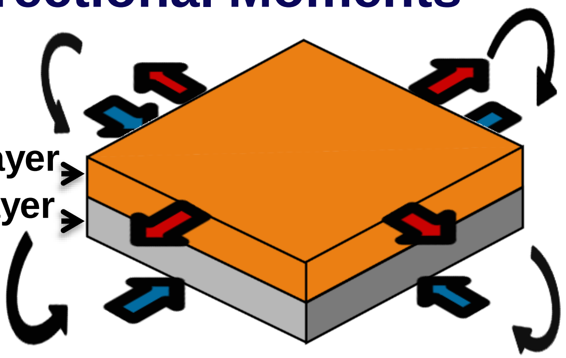
Good wetting was seen on both substrates: SiC/SiC and TZM.

Brazing: Integration of Metals to CMCs for Thermally-Actuated, High Temp. Morphing Composites

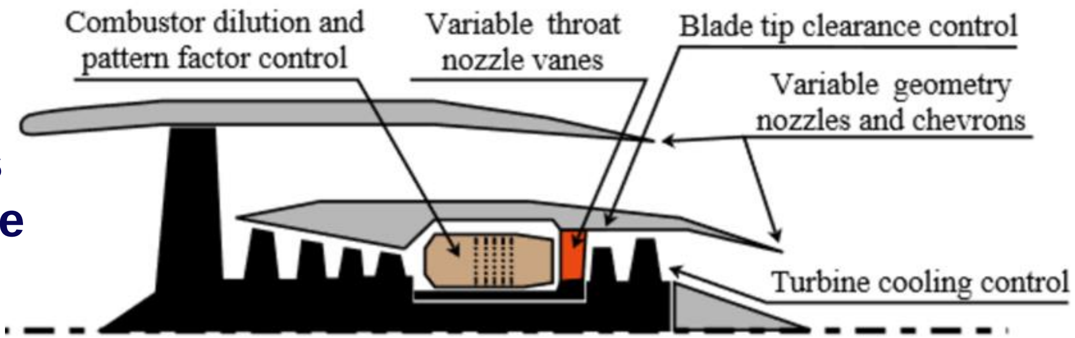
Isotropic Bimorph-Omnidirectional Moments

High expansion layer

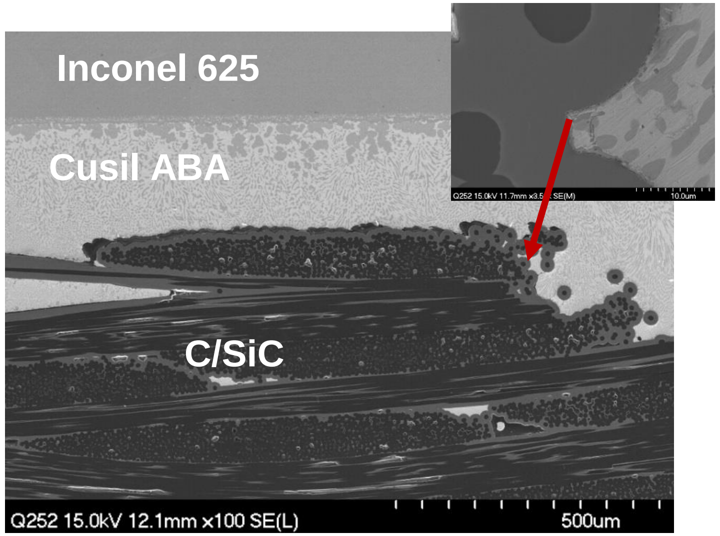
Low expansion layer



Potential Gas Turbine Engine Applications



Morphing of CMC-metallic flap at 1000°C (yellow) compared to R.T.

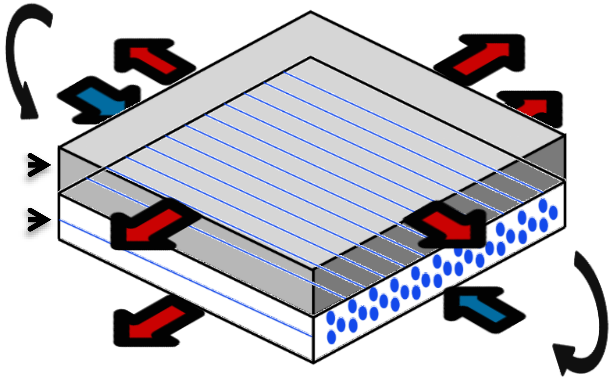


Brazing of C/SiC to Inconel

Composite Construction Allows General Planforms

Metal, high CTE

UD composite, low CTE along fibers

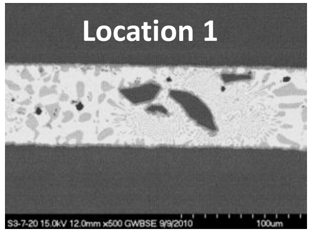


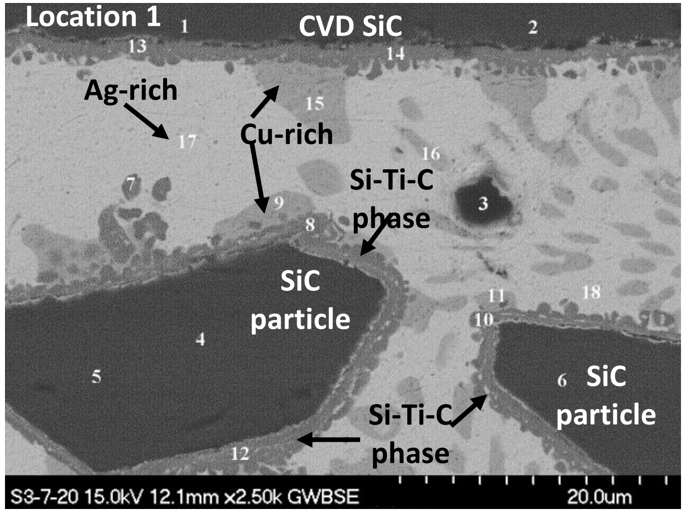
E. Eckstein, M.C. Halbig, and P. Weaver, "Thermally-driven morphing with high temperature composites." In *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1241. 2016.

Bolted flap demonstrated and brazing initiated for fully integrated concepts.

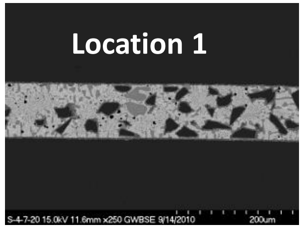
Brazing: Interlayer Property Modifications - SiC Particulate Additions to Ticusil Brazing Paste for CVD SiC to CVD SiC Joining

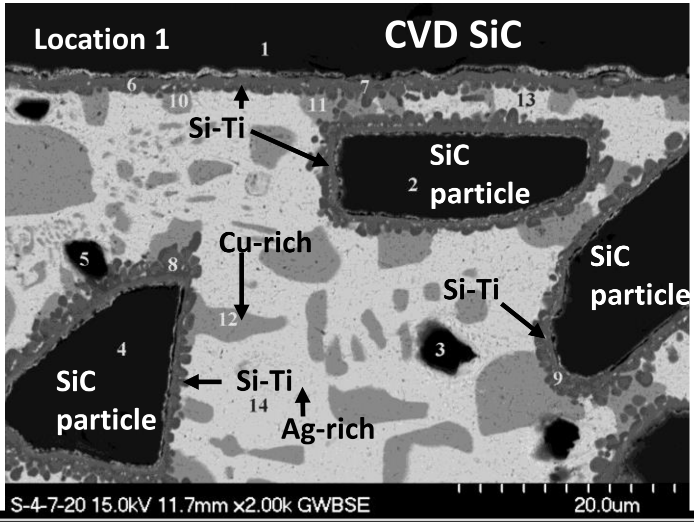
CVD SiC/Ticusil (10wt% SiCp)/CVD SiC





CVD SiC/Ticusil (15vwt% SiCp)/CVD SiC

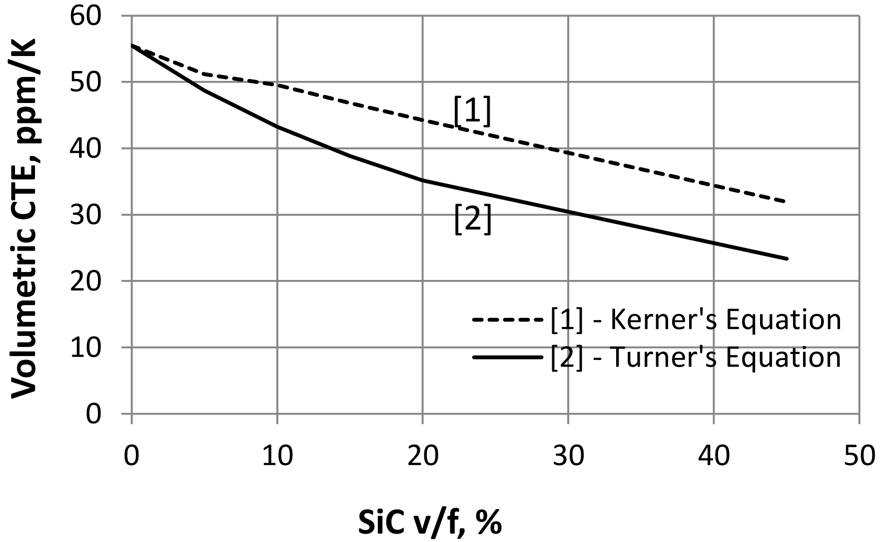




Ticulsil composition in wt. %:
68.8% Ag, 26.7% Cu, and 4.5% T

	Ticusil Paste			
	0 wt% SiCp	5 wt% SiCp	10 wt% SiCp	15 wt% SiCp
	μ ± σ	μ ± σ	μ ± σ	μ ± σ
CVD SiC	3442 ± 71	3304 ± 86	3134 ± 117	3305 ± 119
Braze	**252 ± 58**	**86 ± 5**	**117 ± 52**	**106 ± 31**
CVD SiC	3286 ± 71	3287 ± 95	3241 ± 51	3239 ± 111

Mean (μ) & Standard Deviation (σ) HK of Ticusil Joints



Predicted effect of SiC reinforcement on the volumetric CTE of Ticusil (or Cusil-ABA) braze.

Affects of particulate additions:

- Pulled Ti out of the braze
- Formed Ti-Si-C phases at SiC surfaces
- Decreased the hardness of the braze
- Predicted to lower the volumetric CTE by 40-60% with 40 vol% SiCp.

M.C. Halbig, B.P. Coddington, R. Asthana, and M. Singh, "Characterization of silicon carbide joints fabricated using SiC particulate-reinforced Ag–Cu–Ti alloys," *Ceramics International*, 39, 4 (2013) 4151-4162.

ARCJoinT: Joining of Ceramic Components Using Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Apply Carbonaceous Mixture to Joint Areas

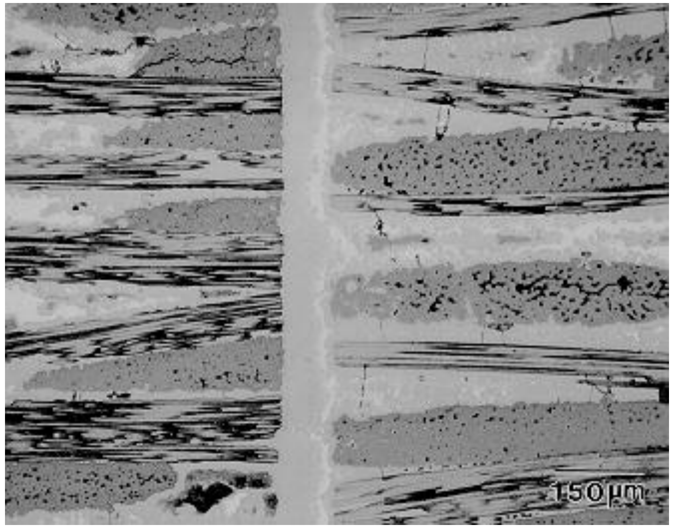
Cure at 110-120°C for 10 to 20 minutes

Apply Silicon or Silicon-Alloy (paste, tape, or slurry)

Heat at 1250-1425°C for 10 to 15 minutes

Affordable and Robust Ceramic Joints with Tailorable Properties

1999 R&D 100 Award
2000 NorTech Innovation Award
(M. Singh)



Joined MI C/SiC Composite

Advantages

- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

Very good quality, high strength bonds are obtained. However, the joining method requires a two-step process and is limited to temperatures <2400°F (1316°C).

Diffusion Bonding and Brazing: Fabrication of Lean Direct Injector Components

Initial effort by a different group was unsuccessful:

Disadvantages of Joining Silicon Carbide with a Silicate Glass Layer

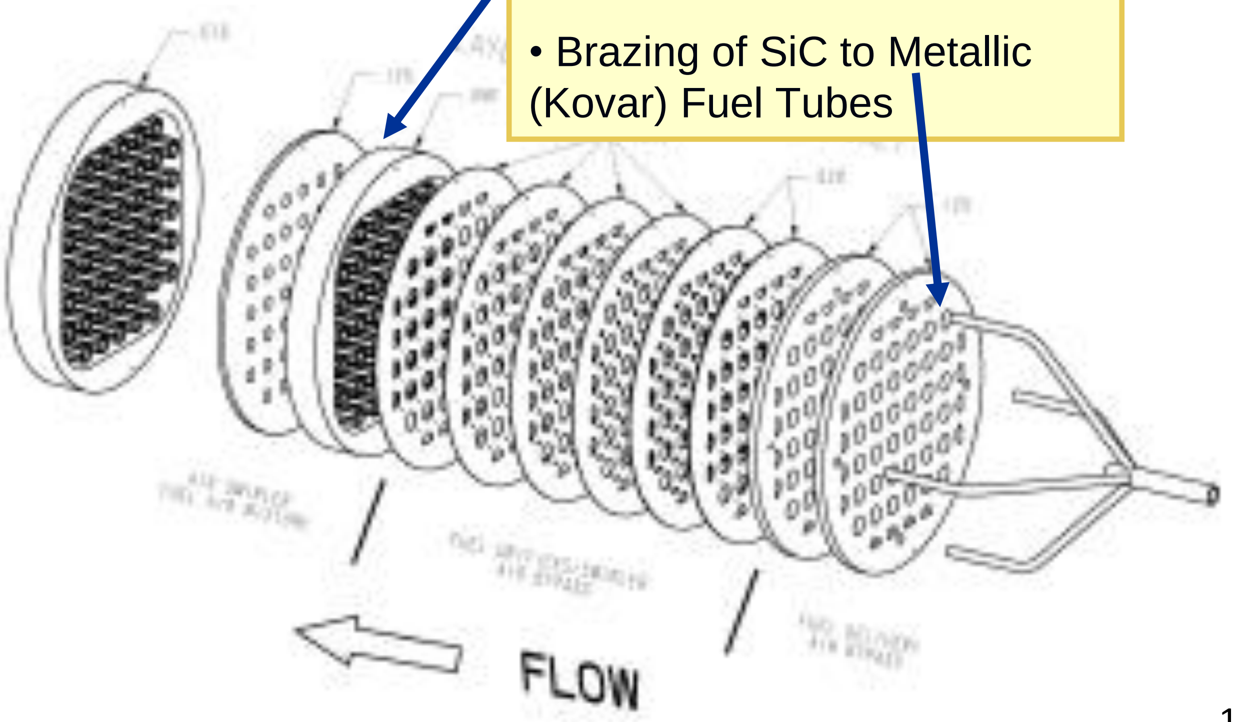
- Difficult to achieve a uniform layer
- Relatively low strength
- Glass flows and fills in holes and edges where it is not desired
- Glass joints were not leak-free

Benefits of Laminated Plates

- **Passages of any shape can be created to allow for multiple fuel circuits**
- **Provides thermal protection of the fuel to prevent choking**
- **Low cost fabrication of modules with complicated internal geometries through chemical etching**

Key Enabling Technologies:

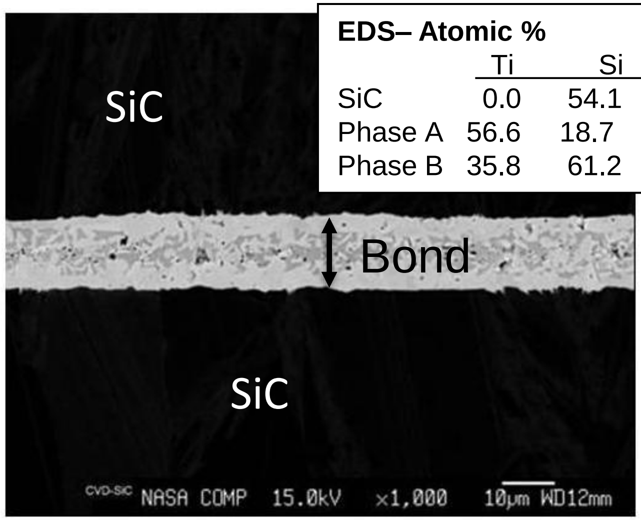
- Bonding of SiC to SiC
- Brazing of SiC to Metallic (Kovar) Fuel Tubes



Diffusion Bonding: CVD SiC to CVD SiC with PVD Ti for Lean-Direct Injector Fabrication

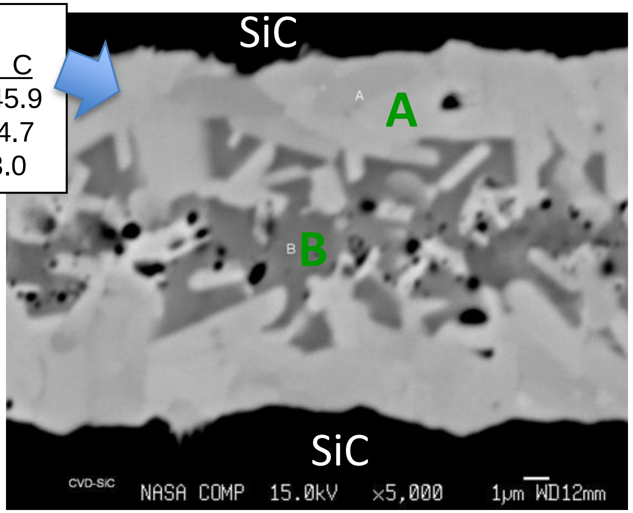
10 μm Interlayer (1200°C, 30MPa, 2 hr, vacuum, cool down 2 ºC/min)

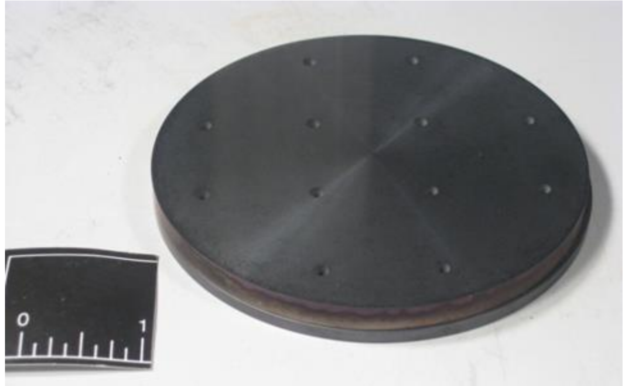
SEM and EDS

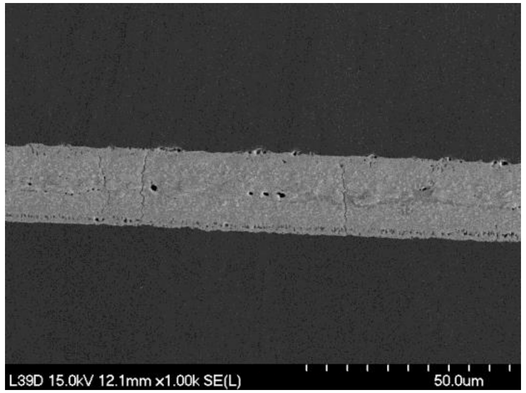


EDS– Atomic %

	Ti	Si	C
SiC	0.0	54.1	45.9
Phase A	56.6	18.7	24.7
Phase B	35.8	61.2	3.0

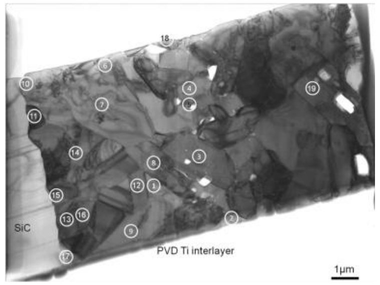




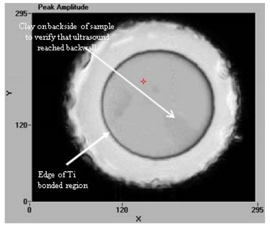


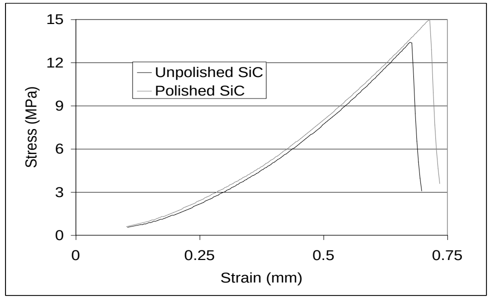
Optimized diffusion bonding conditions were applied to injector sub-elements.

TEM w/SAD



Ultrasonic Immersion and Pull Tests

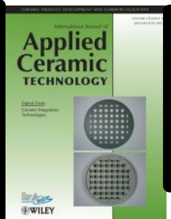




Strengths of 15.0 MPa were twice the requirement.

- **Very good quality bonds are obtained that are uniform and crack free.**
- **The joining process requires high applied loads and flat sub-elements for joining.**
- **However, diffusion bonding is well suited for injector fabrication.**
- **The PVD Ti coating w/diffusion bonding provides a non- flowing joining approach.**

M.C. Halbig, M. Singh, and H. Tsuda. "Integration technologies for silicon carbide-based ceramics for micro-electro-mechanical systems-lean direct injector fuel injector applications." *International Journal of Applied Ceramic Technology* 9, no. 4 (2012): 677-687.

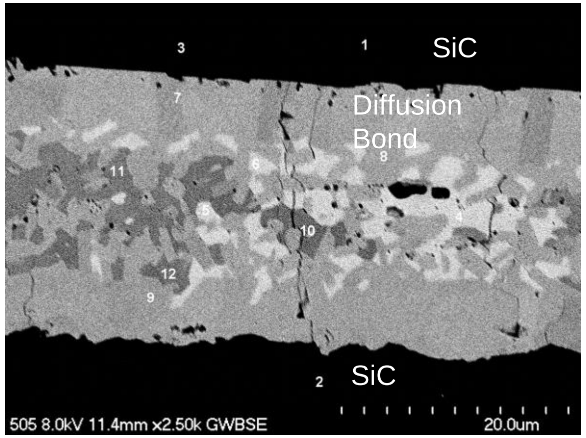


Topical issue on "Ceramic Integration Technologies," July/August 2012 Issue

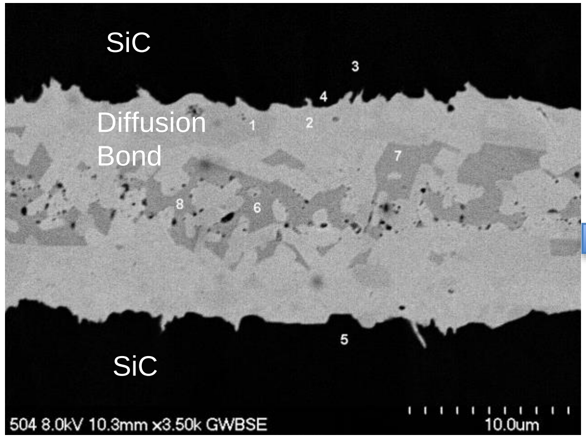
Diffusion Bonding: CVD β-SiC Substrates with Interlayers of Metallic Titanium Foils and PVD Titanium

PVD Ti Interlayer at 1250°C

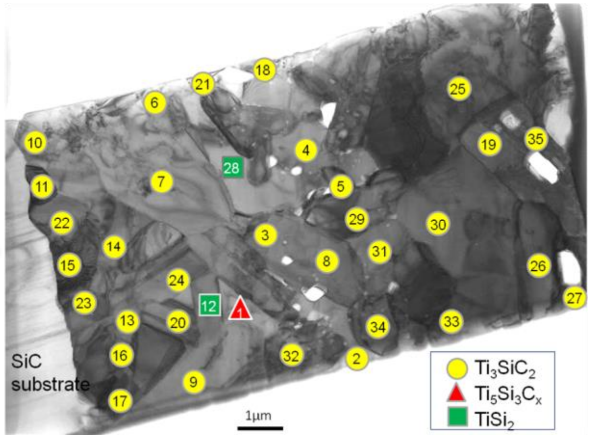
20 micron interlayer and a 2 hr hold



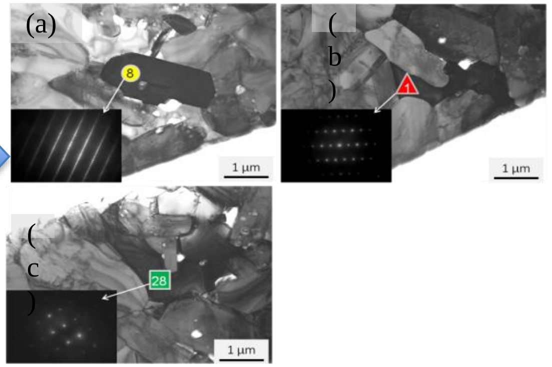
10 micron interlayer and a 2 hr hold



TEM micrograph and determined phases

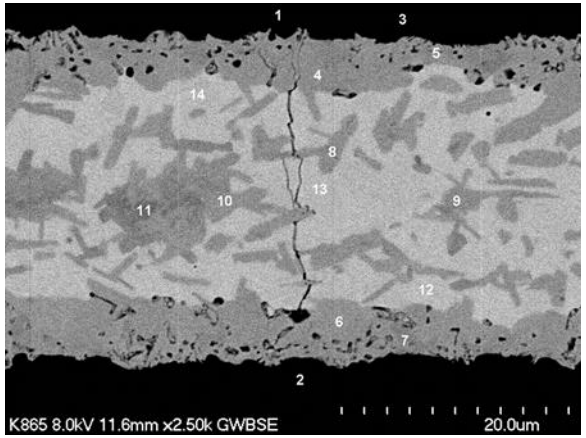


TEM micrographs and SAD patterns: (a) Ti_3SiC_2 (B = [1120]), (b) $Ti_5Si_3C_x$ (B = [7253]), (c) $TiSi_2$ (B = [111]).

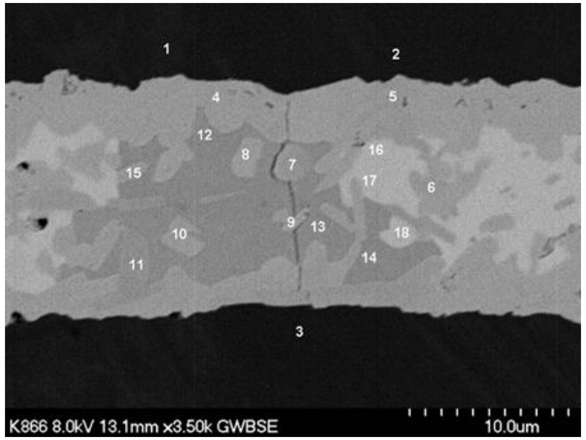


Ti Foil Interlayer at 1200°C

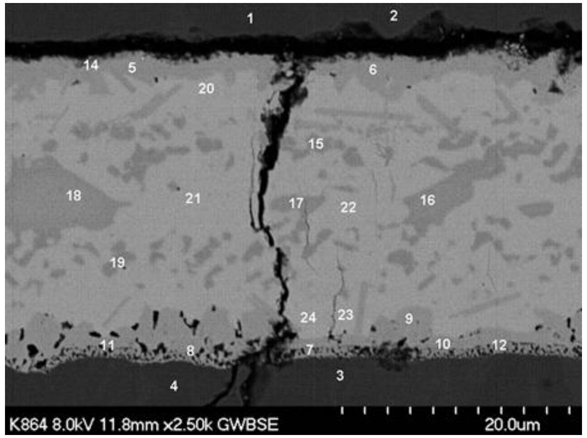
20 micron foil and a 2 hr hold



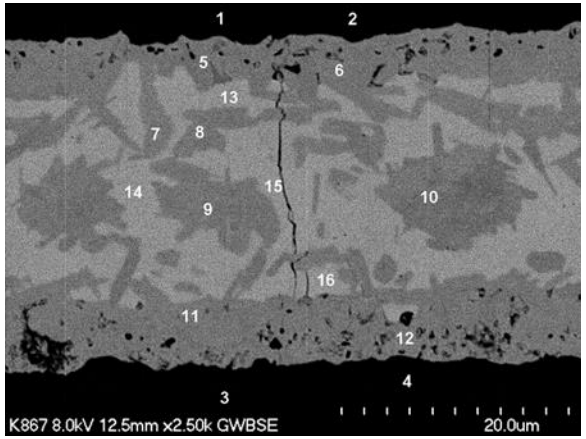
10 micron foil and a 2 hr hold



20 micron foil and a 1 hr hold



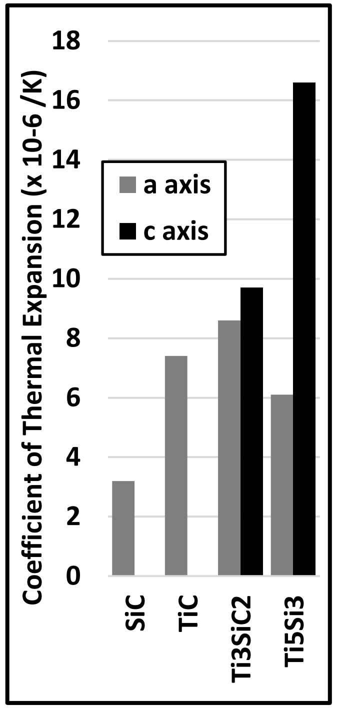
20 micron foil and a 4 hr hold



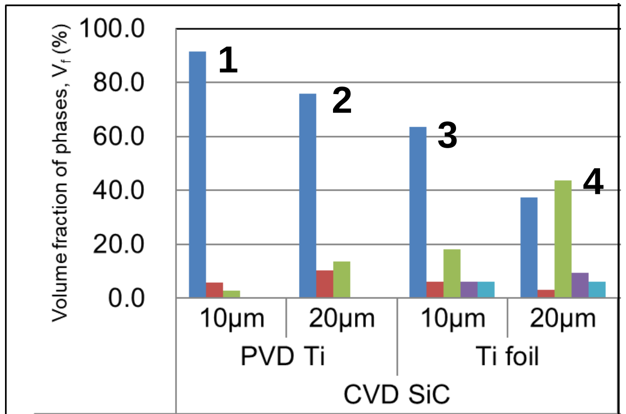
M.C. Halbig, M. Singh, H. Tsuda, and R. Asthana. "Diffusion bonding of SiC ceramics with interlayers of metallic titanium foils and PVD titanium coatings." *International Journal of Applied Ceramic Technology* (2022).

Thinner Ti layers and/or longer processing time can react away intermediate phases and provide crack free or minimally cracked bonds.

Diffusion Bonding: CVD β-SiC Substrates with Interlayers of Metallic Titanium Foils and PVD Titanium

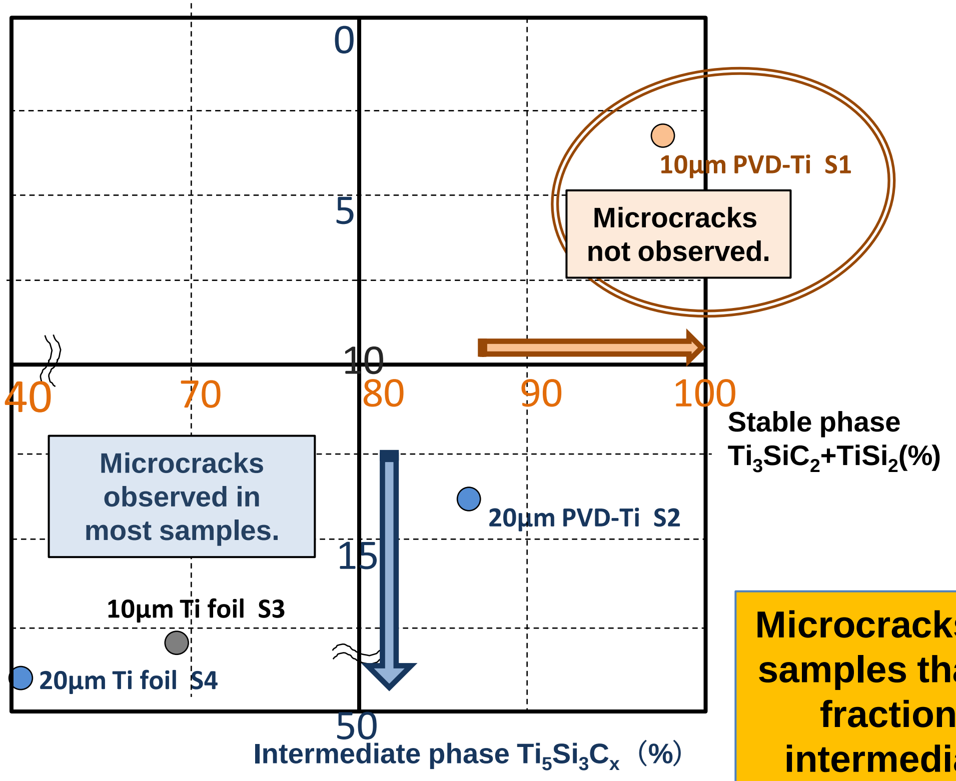


CTEs of the phases.



	10µm PVD Ti	20µm PVD Ti	10µm Ti foil	20µm Ti foil
Ti3SiC2	91.4	75.9	63.6	37.5
TiSi2	5.7	10.3	6.1	3.1
Ti5Si3Cx	2.9	13.8	18.2	43.8
TiC	0.0	0.0	6.1	9.4
unknown	0.0	0.0	6.1	6.3

From TEM analysis, calculated fractions of phases (all 2 hours).



Observed relationship between phase grain fraction and crack formation

Microcracks formed in samples that had high fractions of the intermediate phase $Ti_5Si_3C_x$ and low fractions of the stable phases, Ti_3SiC_2+$TiSi_2$.

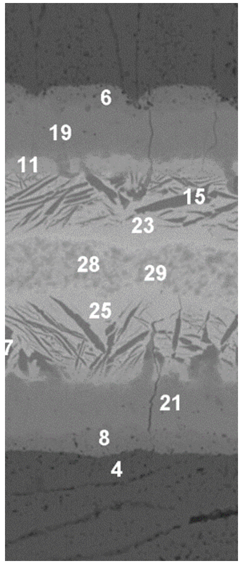
$Ti_5Si_3C_X$ (Ti_5Si_3) is highly anisotropic in its thermal expansion where CTE(c)/CTE(a) = 2.72 (Schneibel et al). Naka et al suggest this is an intermediate phase.

Very good quality bonds are obtained that are uniform and crack free. However, the joining process requires high applied loads and flat sub-elements for joining.

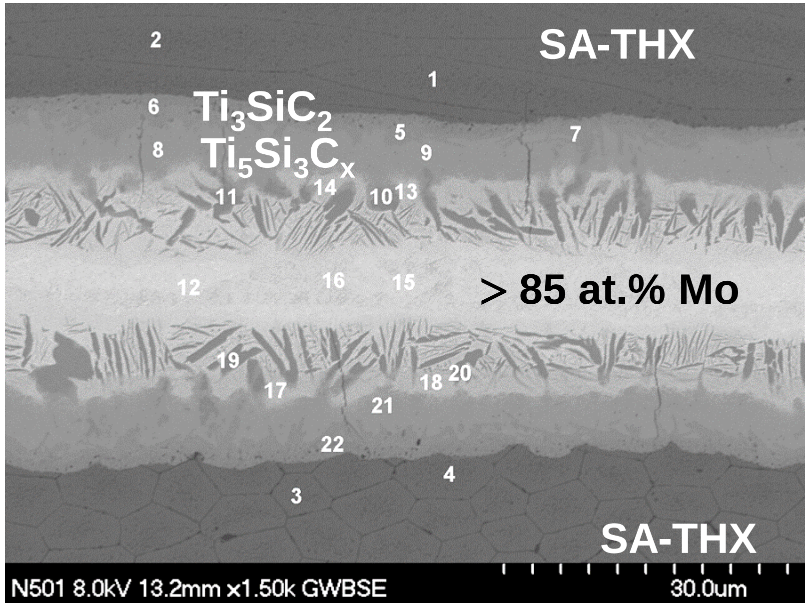
M.C. Halbig, M. Singh, H. Tsuda, and R. Asthana. "Diffusion bonding of SiC ceramics with interlayers of metallic titanium foils and PVD titanium coatings." *International Journal of Applied Ceramic Technology* (2022).

Diffusion Bonding of SiC Fiber-Bonded Ceramics, SA-Tyrannohex™, using Ti/Mo/Ti and Ti/Cu/Ti Interlayers

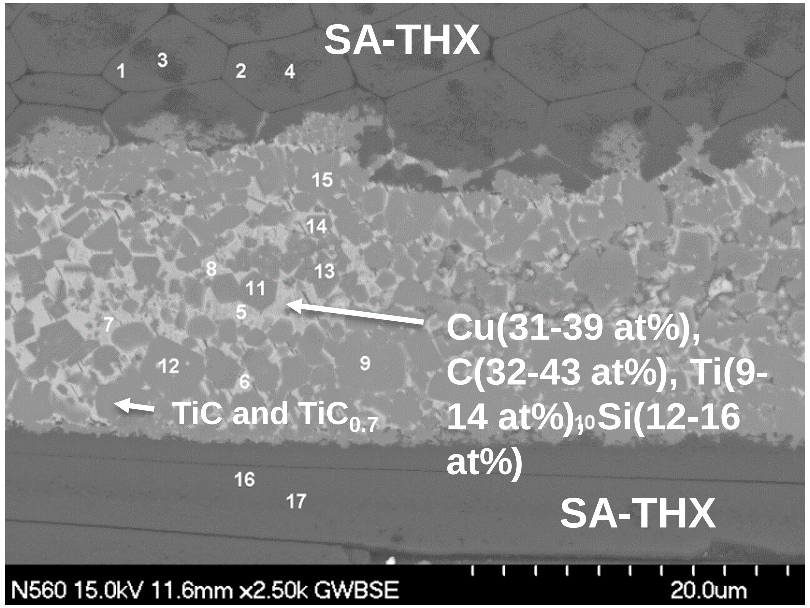
⊥SA-THX



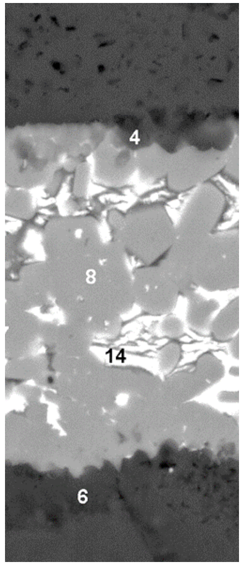
SA-THX w/ fibers ll to joining plane



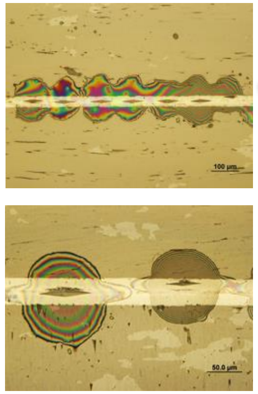
SA-THX w/ fibers ll to joining plane



⊥SA-THX



Microhardness testing



Ti/Mo/Ti Diffusion Bond Layers:

- Lowered Mo bonding temp. from 1500°C to 1200°C (30MPa, 3 hr)
- Introduced a ductile interlayer (half the hardness at the center versus the edge).

Ti/Cu/Ti Diffusion Bond Layers:

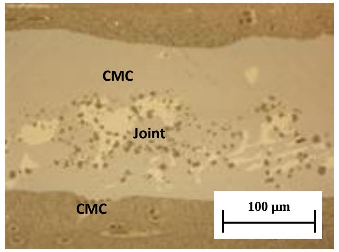
- Cu layer seems to accelerate diffusion and reaction kinetics.
- No micro-cracking as for only a Ti layer where $Ti_5Si_3C_X$ has formed. However, shrinkage cavities are observed.

M.C. Halbig, R. Asthana, and M. Singh. "Diffusion bonding of SiC fiber-bonded ceramics using Ti/Mo and Ti/Cu interlayers." *Ceramics International* 41, no. 2 (2015): 2140-2149.

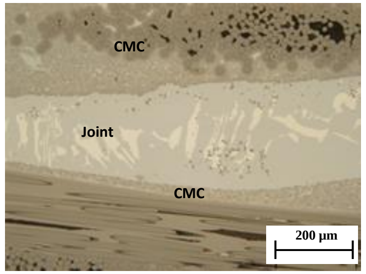
Multi-layers can be used to decrease bonding temperature, increase reaction kinetics, tailor properties, and reduce micro-cracking.

REABond: Joining Various CMCs with Two Si-8.5Hf Eutectic Tapes [210 microns each]

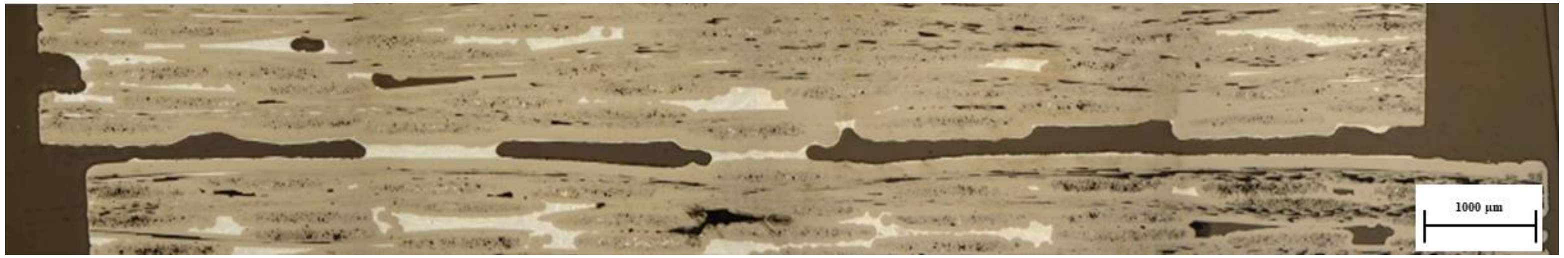
GE Hypercomp II MI SiC/SiC

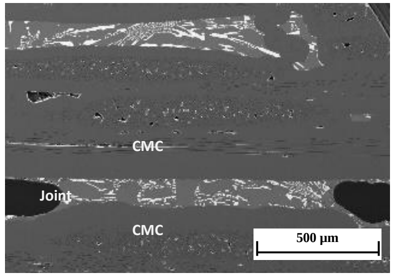


BFG MI SiC/SiC

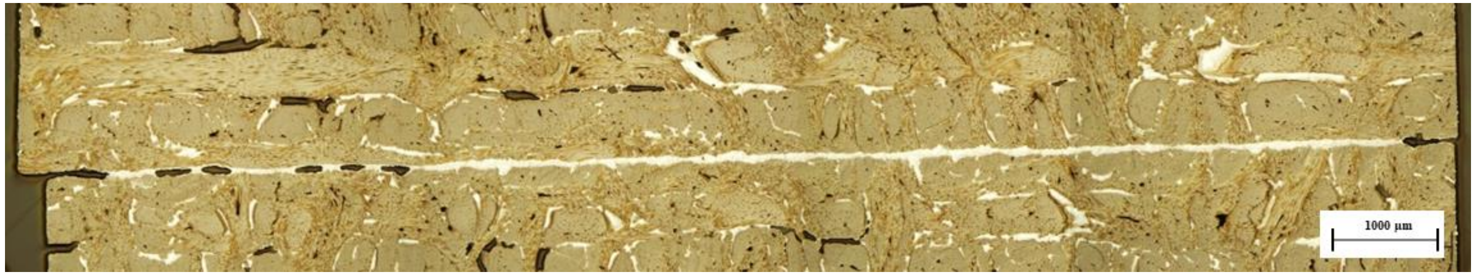


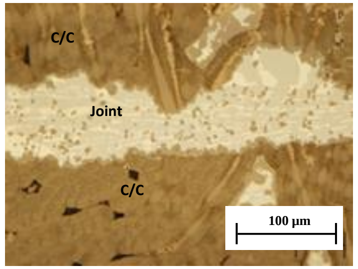
Hyper-Therm CVI SiC-SiC





Goodrich 3-D C/C (3 tapes)





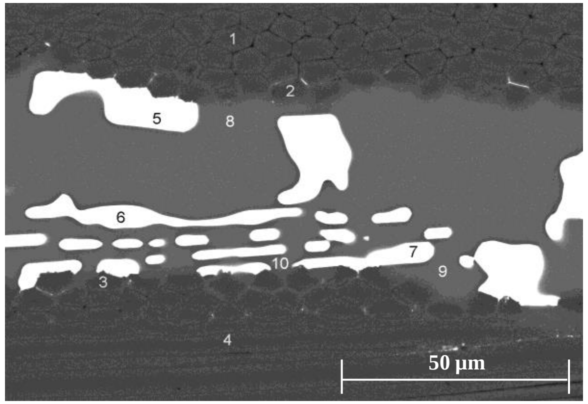
Porous CMCs provide extra challenges by depleting the interlayer material at joining gaps (matrix is infiltrated).

M.C. Halbig, M. Singh, and C.E. Smith. "Refractory eutectic assisted bonding (REABond) technology for joining of high temperature silicon carbide-based composite materials." *International Journal of Applied Ceramic Technology* 19, no. 2 (2022): 1050-1060.

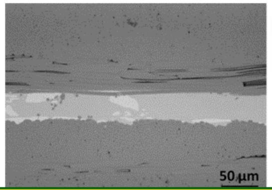
Success with various CMCs with differing surfaces and contours.

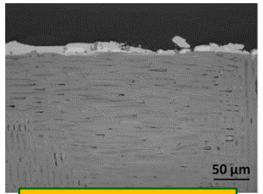
REABond: Joining of SA-Tyrannohex and Mechanical Testing by Single Lap Offset (SLO)

As bonded SA-THX in ‖ orientation (2 tapes)



Joint region after SLO at 1200°C

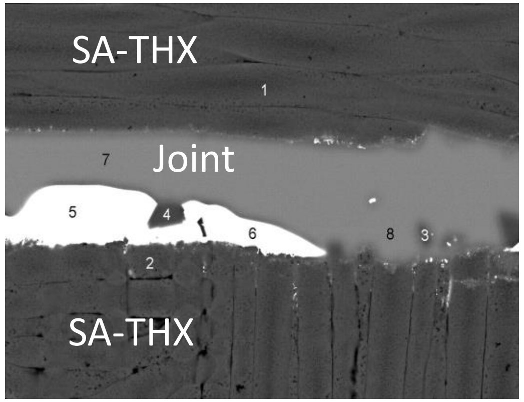


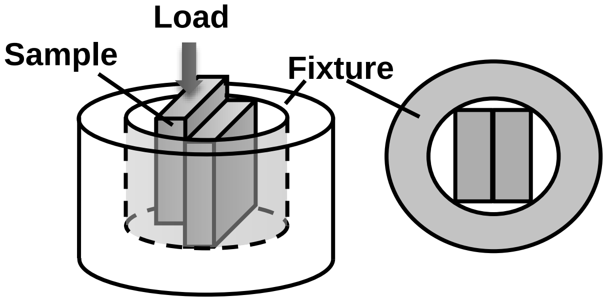


Failure out of view in the composite

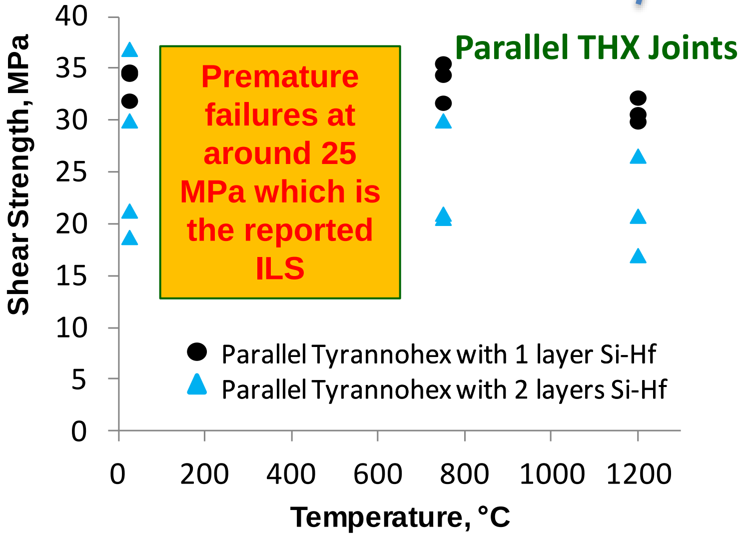
Failure in the joint

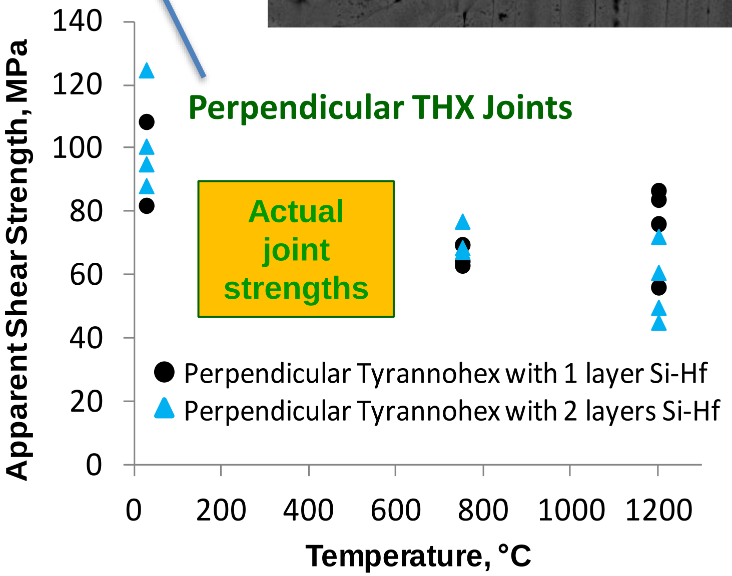
As bonded SA-THX in ⊥ orientation (1 tape)

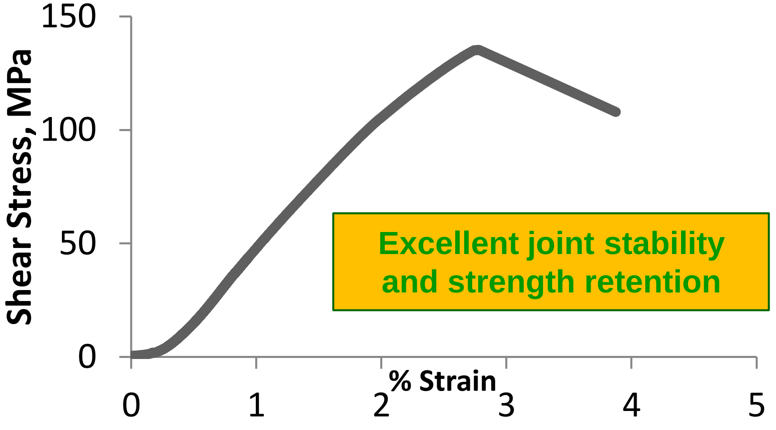




Test configuration for single lap offset shear test







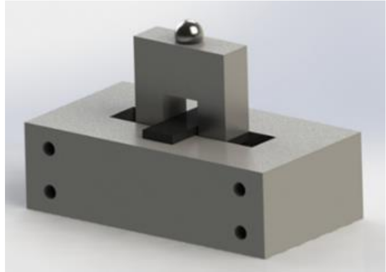
Residual Strength Test
- 350 hr run out at 1200°C and 25 MPa
- tested at 1200°C
- highest strength seen, 135 MPa

Composite interlaminar strengths and fiber architectures can cause premature failures.

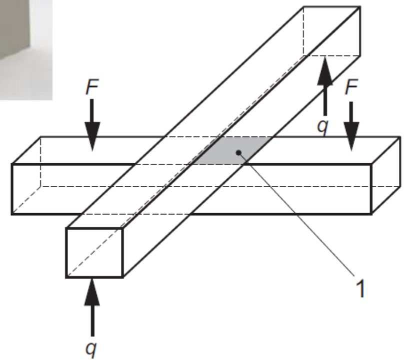
Single lap offset shear test are good for in-house screening. REABond provides high shear and residual strengths.

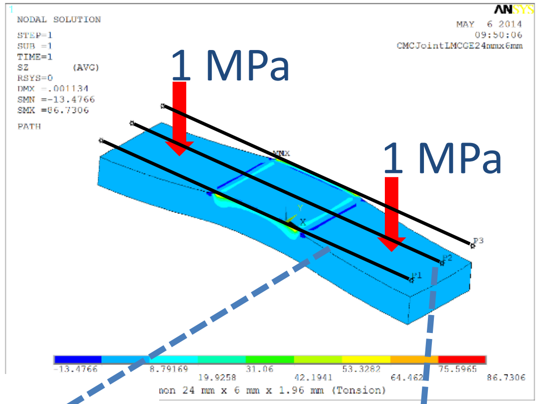
M.C. Halbig, M. Singh, and C.E. Smith. "Refractory eutectic assisted bonding (REABond) technology for joining of high temperature silicon carbide-based composite materials." *International Journal of Applied Ceramic Technology* 19, no. 2 (2022): 1050-1060.

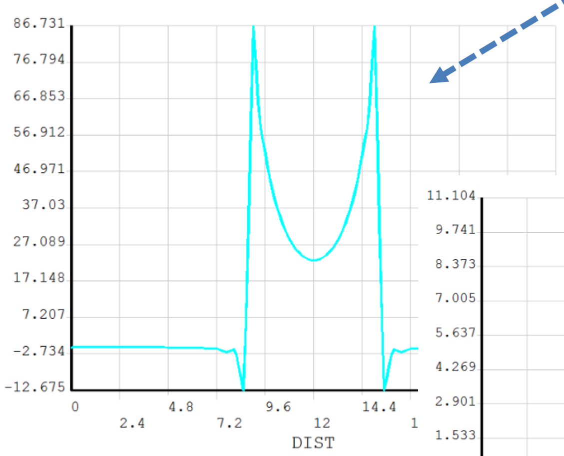
REABond Joining: Testing to ISO 13124

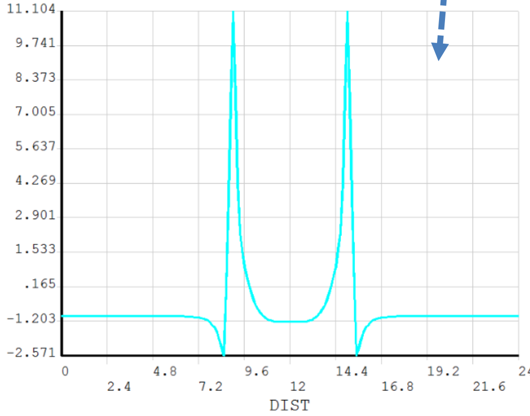


Testing in Tension

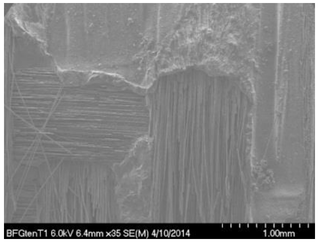




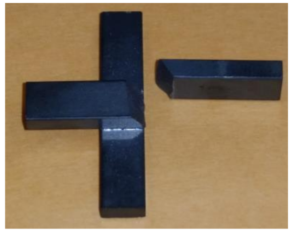




From FEA, Stress (MPA) versus location

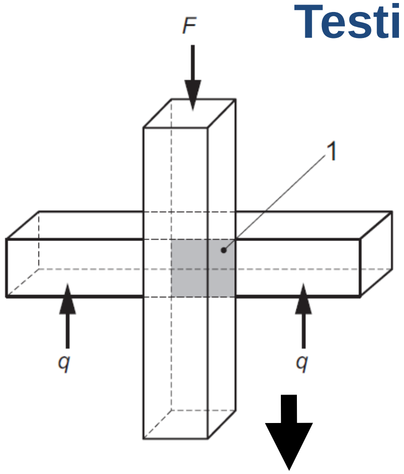


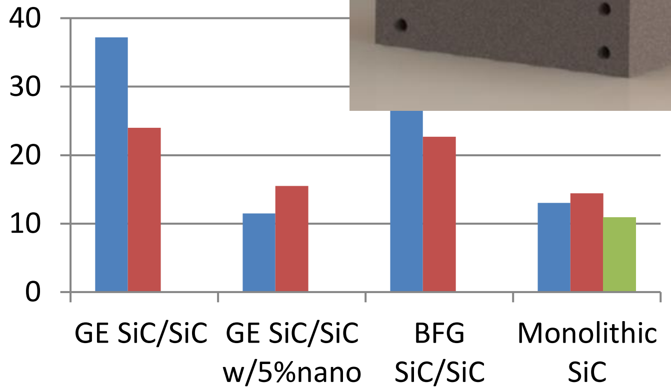
BFG SiC/SiC Failure

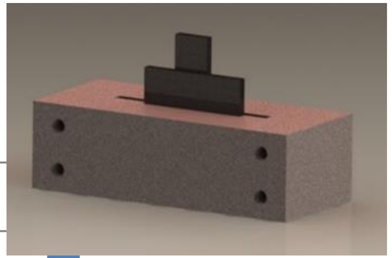


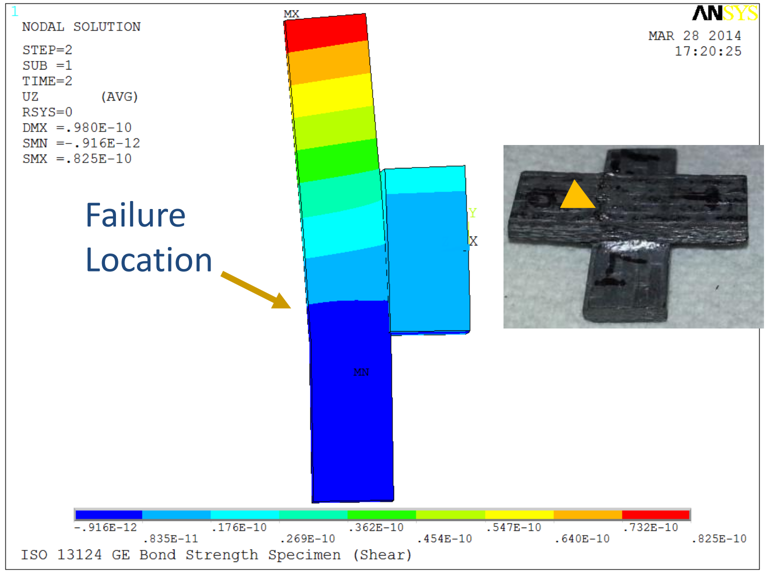
SiC Failure

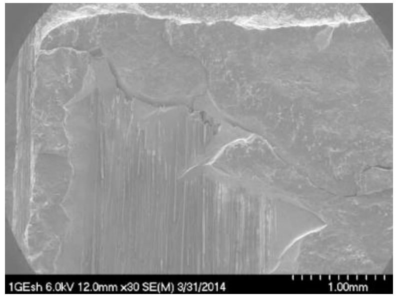
Testing in Shear



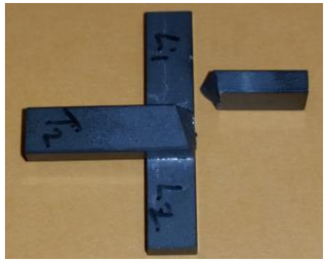








BFG SiC/SiC Failure



SiC failure

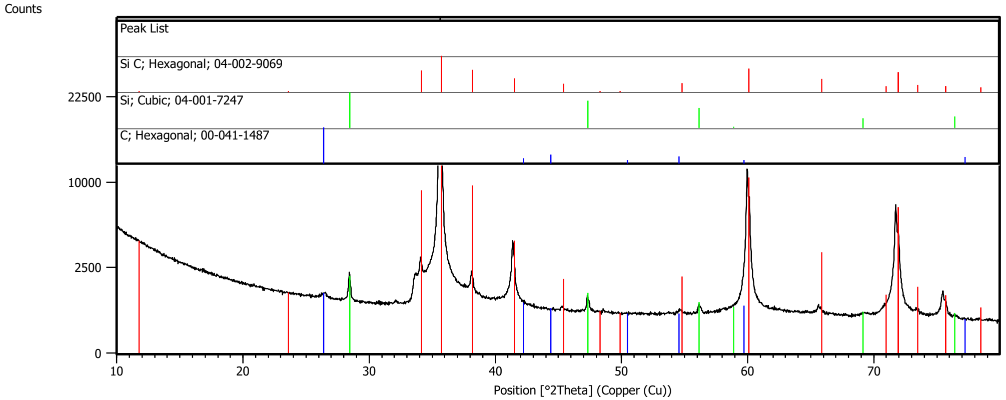
M.C. Halbig, M. Singh, and J. Lang. "Development of High Temp. Joining and Thermomechanical Characterization Approaches for SiC/SiC Composites." *Advanced Processing and Manufacturing Technologies for Nanostructured and Multifunctional Materials II, Vol. 36, Iss. 6* 6 (2015): 3.

The peak stresses, premature failures, low strengths, and fractures in the substrates demonstrate the challenges in having well developed and reliable test methods.

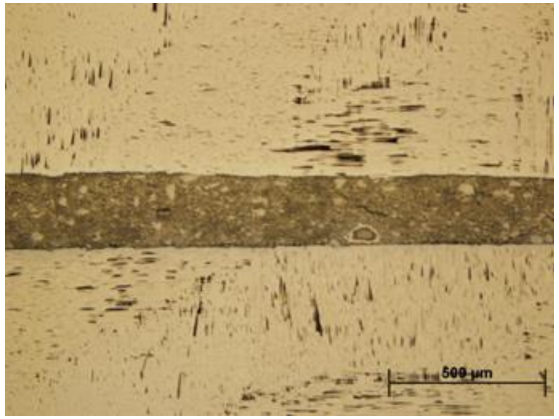
SET: Single-Step Elevated Temperature Joining
- Higher Temperature Capable C, Si, and SiC-Based Pastes

Approach: 30 mil thick green tapes of SiC, Si, and carbon powders of varying particle sizes, also several other additives.
Benefits: high temp. capability and one-step SiC formation.

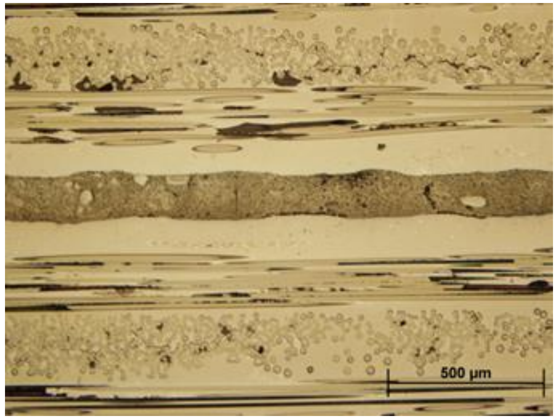
X-Ray Diffraction analysis of three slurry compositions heat treated at 1450°C for 30 min.



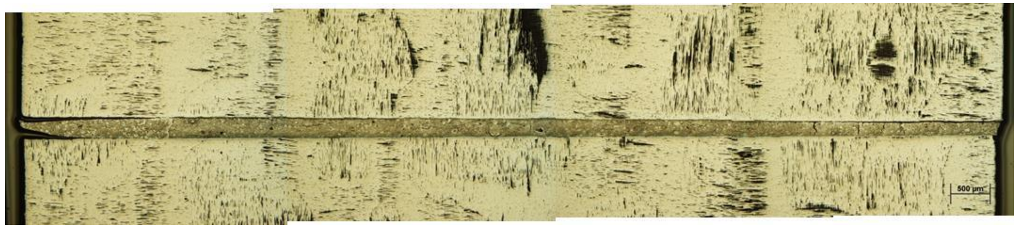
	SemiQuant (%)		
Composition	**SiC**	**Si**	**C**
J5A+Si	**99**	**1**	**0 - nearly complete SiC conversion**
J5A+N1+Si	91	9	1
J5A+N2+Si	92	7	1



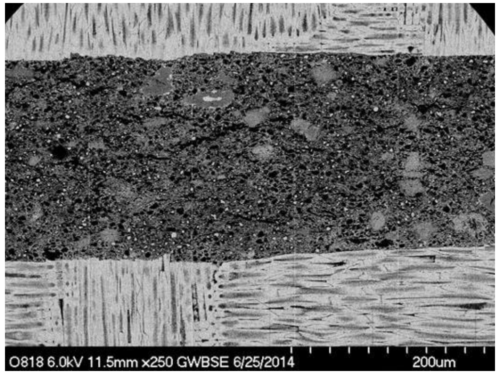
J5A+N2+Si Joining of SA-THX (⊥orientation)



J5A+N1+Si Joining of SiC/SiC



Perpendicular SA-Tyrannohex with N1+J5A+Si



- High conversion to SiC provides one-step SiC formation.
- Offers low stress joining for complex shapes.
- High temperature capability (>2400°F) due to absence of free silicon.

Summary/Conclusions

- Good quality joints are obtained from all five CMC to CMC joining methods: Brazing, ARCJoinT, Diffusion Bonding, REABond, and SET.
- Diffusion Bonding is the most restrictive joining approach requiring flat shapes, relatively smooth surfaces and high pressures.
- Brazing, REABond and SET approaches are the most versatile allowing for tailored interlayers for pressureless joining of complex shapes with smooth or rough surfaces in one-step processing.
- Particulate additions to the braze were shown to modify the hardness and thermal expansion of the joint.
- Mechanical tests to include ISO 13124 and single-lap offset shear are being used but additional analysis and improved test methods are needed.
- Selection of proper joining technologies is critical for the successful development and applications of ceramic components in a wide variety of current and emerging applications.
- These approaches offer many opportunities for development and implementation of turbine engine and other aerospace components with improved performance, lower emissions, lighter weight, and thermal management.

Acknowledgements

- This work was support by the NASA aeronautics projects of:
  - Transformative Tools and Technology (TTT)
  - Revolutionary Vertical Lift Technology (RVLT, previously Subsonic Rotary Wing)
  - Hypersonics Technology Project (HTP).
- Thank you to John Setlock at NASA GRC for preparing REABond tapes.
- Thank you to Ron Phillips (retired) for ISO 13124 testing.
- Thank you to all collaborators/co-authors as noted in the referenced papers.